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LEVEL II

SCATTERED LIGHT PHOTOELASTIC ANALYSIS OF A PROJECTILE BULKHEAD TO STRUCTURAL CASE JOINT

MILOSLAV BENICEK and JIRO ADACHI
ENGINEERING MECHANICS DIVISION

October 1979

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ARMY MATERIALS AND MECHANICS RESEARCH CENTER
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ABSTRACT

Photoelastic stress analysis of the bulkhead-to-structural case pin joint of a projectile was carried out using the scattered light technique. Analysis provided three-dimensional stress distributions in critical areas of the joint including the pinhole, pin bearing surfaces, and joint bearing surfaces. Stress gradients through the wall were found to be large; however, stress concentrations were found to be moderate with a maximum value of 3.7.

CONTENTS

I. INTRODUCTION

In advanced artillery shells, the most severe stresses and stress concentrations are encountered in the pins, pinholes, or at the fillets of the joints. There is always concern that failure will start in these areas.

Since practical and accurate mathematical three-dimensional analysis of the pin, the pinhole area, and the joint is beyond the present state-of-the-art, it is necessary to use other means to predict stress values when the need arises. For this reason a photoelastic stress analysis of the rear joint of a recent projectile was undertaken to examine the stress conditions throughout the joint, particularly at contact areas of the pin and pinhole walls and on the mating surfaces of the joint where high stress gradients and stress concentrations were expected to arise.

The scattered light technique of photoelasticity was used for this investigation. With this technique stress variations throughout the specimen thickness can be determined in three dimensions without slicing the model, allowing the possibility for studying the effect of different pin interference values on the stresses merely by change of pins and/or pin interference.

II. EXPERIMENTAL PROCEDURE

A. Frozen Stress Model Preparation

The rear joint has an outside diameter of 8 inches and inside diameter of 7.6 inches. There are sixteen pins equally spaced around the circumference. To simplify the analysis a segment representing one-sixteenth of the periphery with the pin centrally located was modeled, see Figure 1. The use of this two-dimensional specimen greatly simplified fabrication, made possible the use of a large-scale specimen, and simplified loading and testing while preserving the key features of the joint.

To simulate combined axial load and torque, the contact surfaces between the joined components were angled at 9°30' from the longitudinal, as shown in the figure. Stress distributions through the thickness of the specimen were more easily obtained with the model scaled up to 2.5X. The model material was Photolastic PLM-4B modified for scattered light application. Model components are shown in Figure 2. A final surface finish of 8 microinches was obtained by grinding. The model was fabricated with precision so that the joint contact surface would be in full contact with the model pin inserted with a size-to-size fit. Although the polariscope system allowed photographing the model under load, the stress freezing method was used because it was mechanically simpler. The stress freezing of the model and a calibration tension specimen was carried out in a special temperature-controlled convection oven following heating and cooling cycles recommended for the given material.

The axial load was applied to the end of the model by means of a deadweight loading system (see Figure 3) which transmitted the load through a column (A) and ball (B) into the triangular loading plate (C); the spherical ball, free to roll between the loading rod and plate, ensures a vertical load at all times. Plastic

rollers (D) provide lateral support to resist any tendency toward gross bending or buckling of the specimen, particularly at the higher temperatures. A 1/8"-thick strip of silicone rubber between the aluminum loading plate and the surface of the model smoothed out localized high contact stresses and reduced surface shear stress resulting from differential thermal deformation. A scaled-down load was applied to the model. This load of 19.7 pounds was determined from the relationship

$$P_m = \frac{P_p E_m L_m t_m}{n E_p L_p t_p}$$

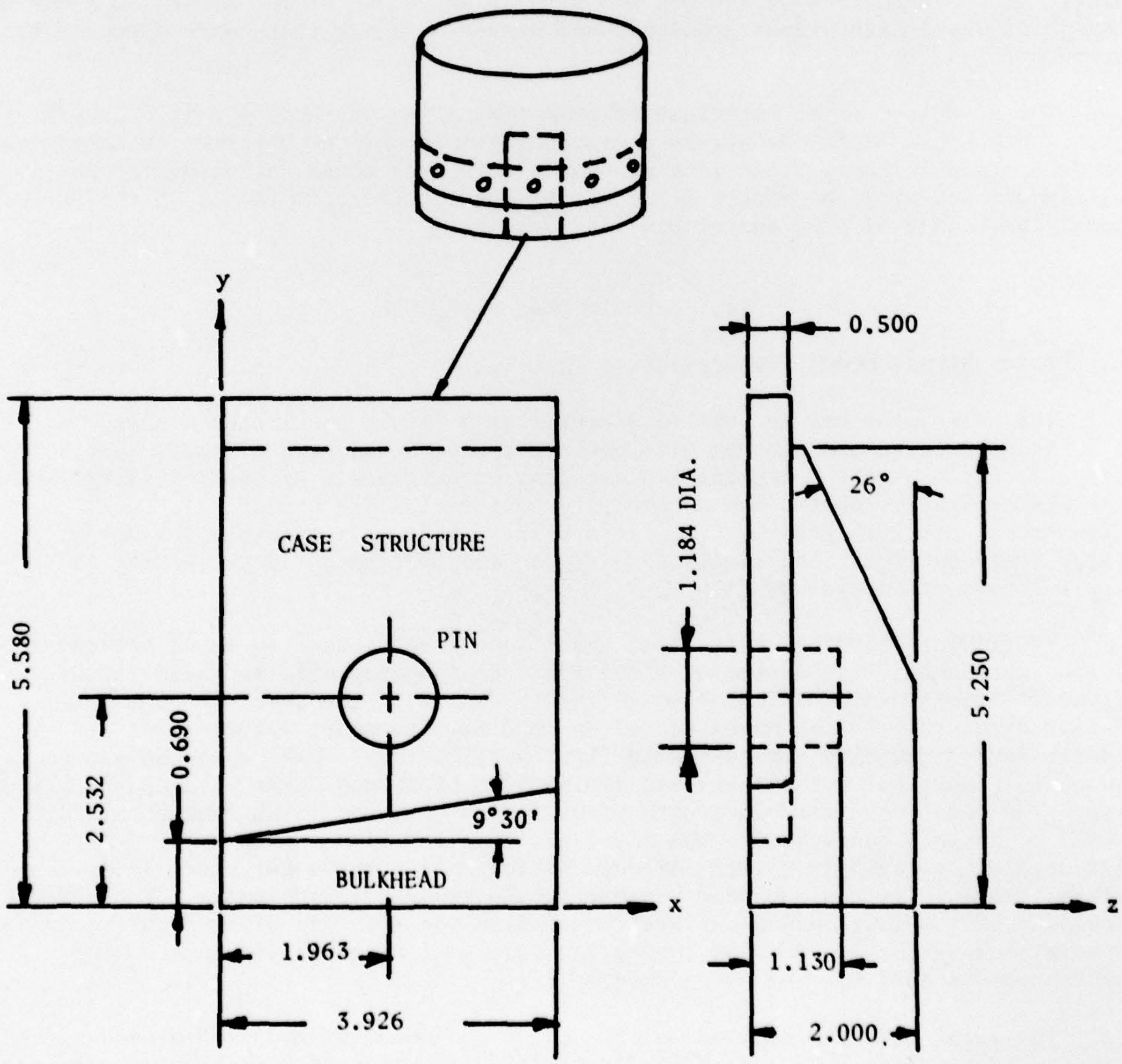

Figure 1. Two-dimensional photoelastic model of rear joint - 2.5X scale.

for which

P_m = axial load applied to model at joint (lb)

P_p = axial load applied to prototype at joint (lb)

E_m = tensile modulus of elasticity for model at the stress freezing temperature of 250 F (lb/in.^{2})

E_p = tensile modulus of elasticity for prototype 4340 steel (lb/in.^{2})

L_m = model width (inch)

L_p = dimension in the peripheral plane of the prototype (inch)

t_m = model thickness (inch)

t_p = prototype thickness (inch)

n = number of pins

was applied to the model.

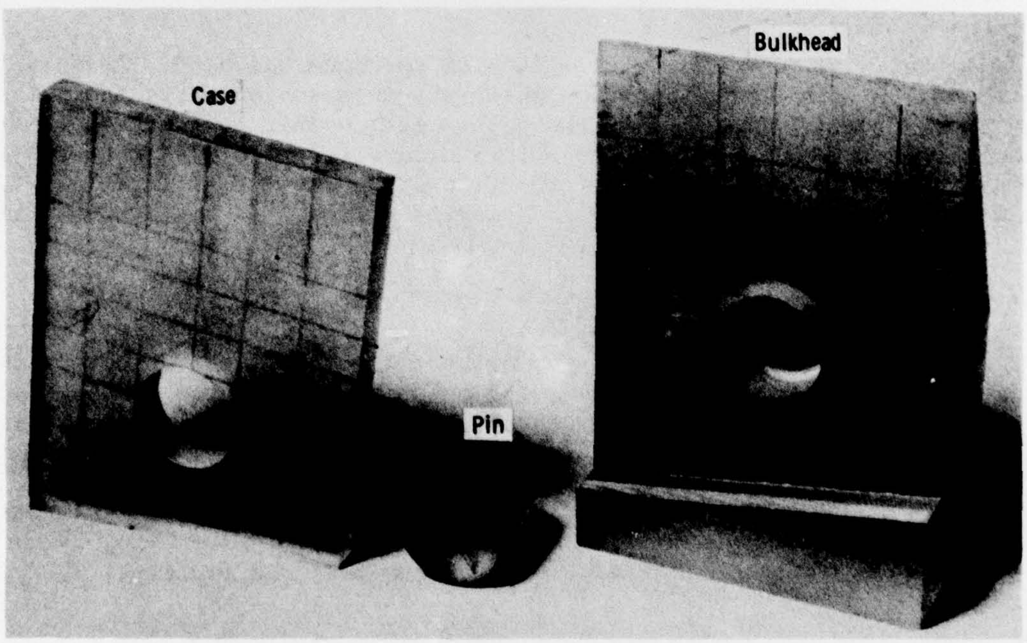

Figure 2. Machined components of the specimen.

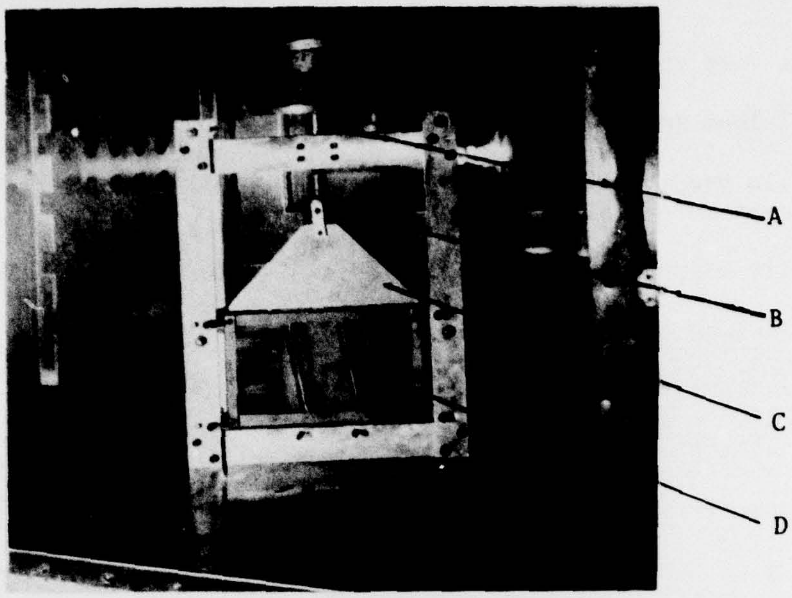

Figure 3. Assembled model in loading fixture.

B. Calibration of Model Material

To calibrate the model material a tension specimen was used. An axial load of 6.65 lb was applied to the specimen which was then subjected to the same stress-freezing cycle as that employed for the joint model. This load was chosen to produce the largest number of fringes to insure accurate determination of the fringe constant without exceeding the proportional limit of the PLM-4B material. Figure 4 shows the calibration curve based on 13 observed fringes. A calibration value of 2.16 psi/fringe/inch was obtained.

C. Scattered Light Fringe Photographs

The theory of scattered light is described in numerous references[1-4] and will not be discussed here. The stress-frozen model was mounted to the head of the polariscope and immersed in a glass-walled tank containing index-matching fluid as shown in Figure 5. The light beam from a 15-MW CW He-Ne gas laser was passed through a cylindrical lens system to expand the beam into a sheet of light 1.5 inches wide and 0.060 inch thick which entered the polariscope and model from below. The fringe patterns were recorded on 4 in. × 5 in. film using 3- to 7-minute exposures on Polaroid film 55 P/N and 3- to 6-second exposures on Polaroid film 57.

1. SRINATH, L. S., and FROCHT, M. M. *Potentialities of the Method of Scattered Light.* Proc. International Symposium of Photoelasticity, Pergamon Press, New York, 1962.
2. JESSOP, H. T. *The Scattered Light Method of Exploration of Stresses in Two- and Three-Dimensional Models.* Brit. J. Appl. Phys., v. 2, no. 9, 1951.
3. SWINSON, W. F., and BOWMAN, C. F. *Application of Scattered Light Photoelasticity to Doubly Connected Tapered Torsion Bars.* Experimental Mechanics, v. 6, no. 6, June 1966, p. 297-305.
4. SWINSON, W. F., ROLSON, W. F., and GRIFFIN, J. R. *Scattered Light Photoelastic Analysis of Epoxy Glass Structures.* U.S. Army Missile Command, Redstone Arsenal, Technical Report RL-72-16, December 1972.

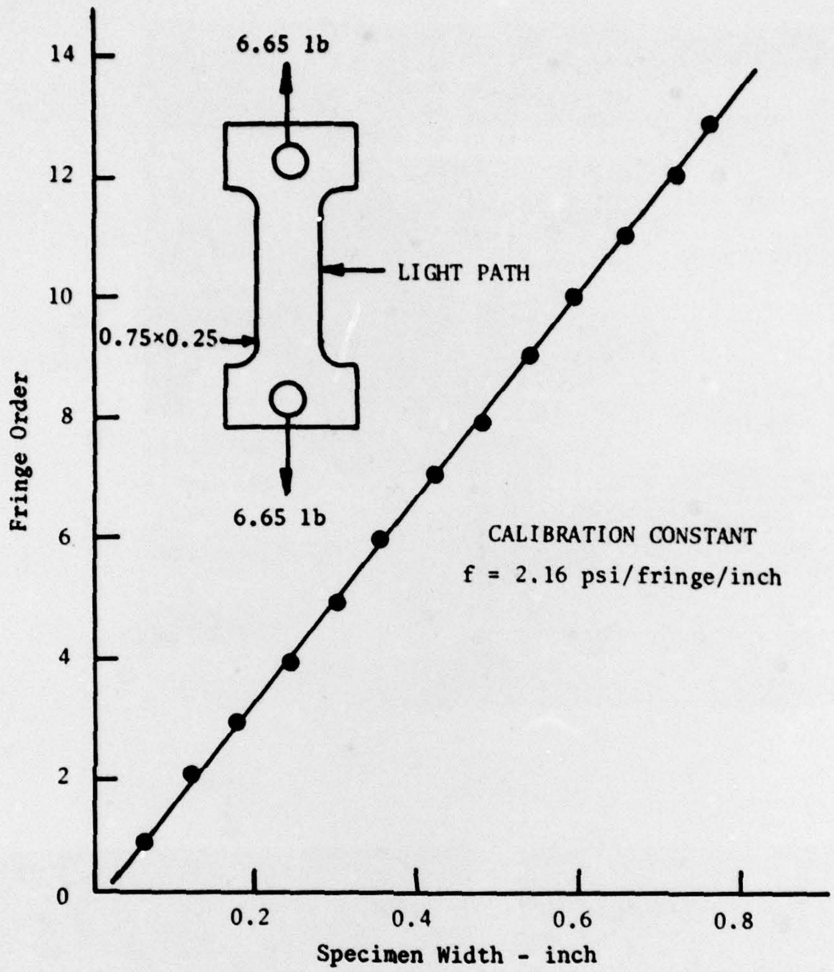

Figure 4. Calibration curve.

Laser beam axis and the glass wall of the immersion tank are fixed normal to the camera axis. The head to which the model was mounted allows rotation of the model about the laser beam axis and translation along two orthogonal axes in the horizontal plane. These motions allow the sections of the model illuminated by the laser and the angle between camera and model to be varied easily. Typical fringe patterns are shown in Figure 6.

The fringe photographs were analyzed using a microdensitometer to measure and record fringe number versus location. These data were translated into stress values by using the stress optic law $(p-q) = f(dn/ds)$, where f is the fringe constant of material, dn is an increment in the fringe order, and ds is an interval in the optical path. Distortion and obliteration of fringes occurred in some areas of the specimen because of deformation and mottling during the stress-freezing process. However, low fringe density along the y direction and light diffusion in some areas were mainly responsible for not obtaining the $\bar{\sigma}_y$ stress at some points of interest.

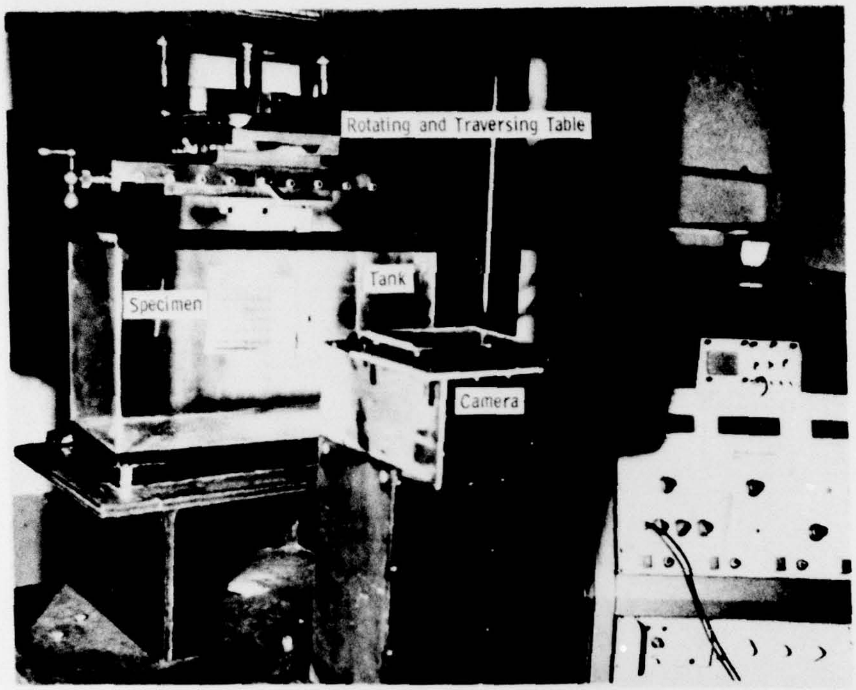

Figure 5. Test specimen mounted in polariscope.

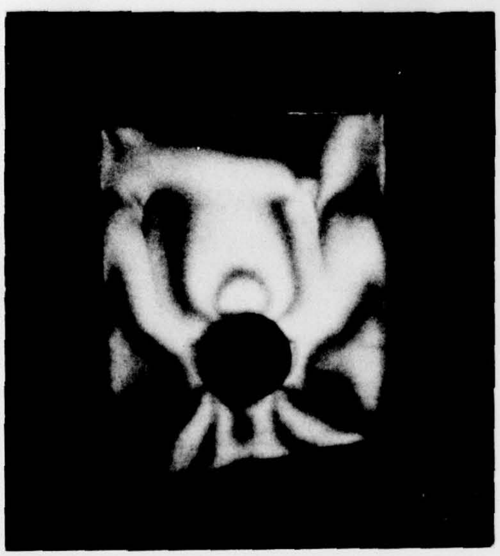

Figure 6a. Isochromatics of stress-frozen specimen.

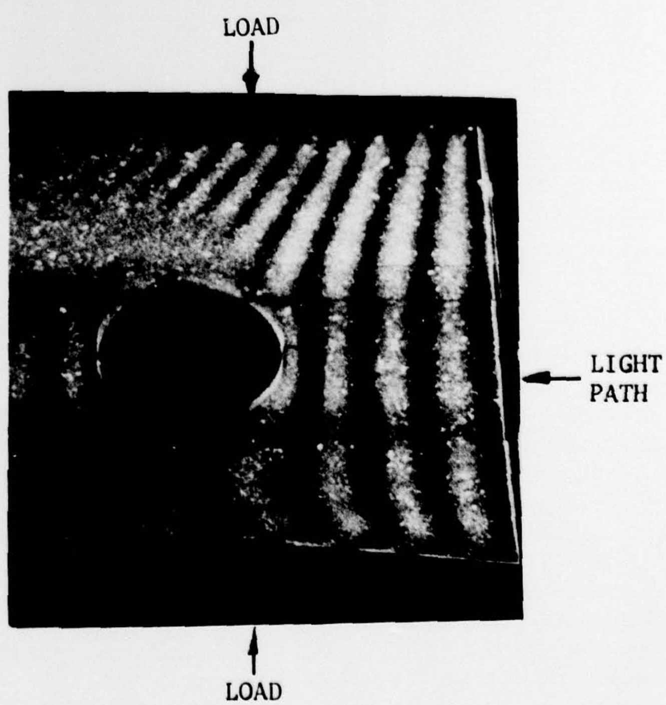

Figure 6b. Scattered light fringes of stress-frozen specimen.

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Photoelastic stress analysis of the bulkhead-to-structural case pin joint of a projectile was carried out using the scattered light technique. Analysis provided three-dimensional stress distributions in critical areas of the joint including the pinhole, pin bearing surfaces, and joint bearing surfaces. Stress gradients through the wall were found to be large; however, stress concentrations were found to be moderate with a maximum value of 3.7.

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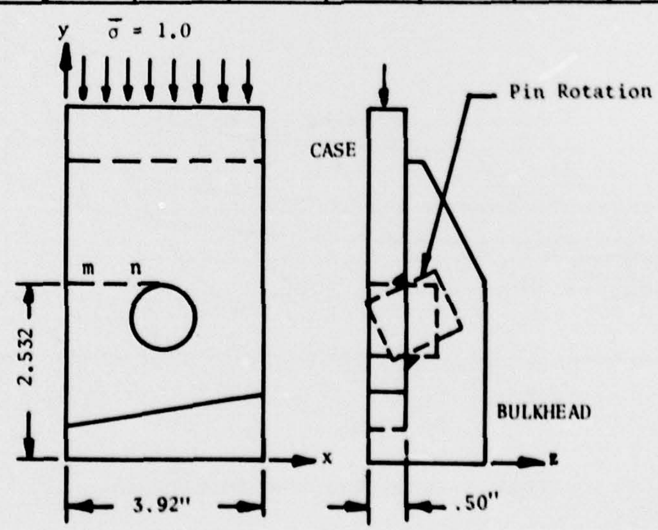
III. EXPERIMENTAL RESULTS

A. General

Stress results obtained are shown in Figures 7 through 10 and in Table 1. These results were obtained using scattered light photoelasticity in a two-dimensional plane-stress problem. Since in this case only in-plane normal stress perpendicular to the direction of light propagation contributes to the fringe formation, values of this stress are obtained directly and no stress separation is required. Stress variations through the specimen thickness were obtained by traversing the light along the z direction. Only the information of significant interest to the current problem are presented here. The primary interest was phenomenological. It was necessary to obtain an insight into how the pin behaved under the axial setback loads and the effect of this behavior on the distribution of stresses in the joint region. Of further interest and of direct and immediate relevance to the problem was the magnitude and location of high stresses and strains.

Table 1. DISTRIBUTION OF $\bar{\sigma}_y$ STRESS THROUGH SPECIMEN THICKNESS AND ALONG LINE mn

z / x	$\bar{\sigma}_y$ (COMPRESSION)						
	0.000"	0.060"	0.013"	0.250"	0.350"	0.450"	0.500"
0	0.89	0.87	0.83	0.55	0.67	0.94	1.10
0.25	.91	.89	.85	.55	.67	.92	1.08
0.50	.95	.92	.81	.72	.72	.96	1.12
0.75	.83	.82	.81	.75	.75	1.20	1.45
1.00	.89	.87	.81	.72	.81	1.20	1.50
1.25	.93	.89	.81	.77	.87	1.60	1.90
1.50	.40	.60	.85	.72	1.10	1.80	2.30
1.75	.48	.58	.77	1.10	1.70	2.40	2.80
1.96	.45	.55	.76	1.30	1.90	3.00	3.70



In presenting the data, the stresses σ have been converted into dimensionless form $\bar{\sigma}$ by dividing the actual stresses by the average nominal stress determined at the horizontal cross section 1.5 inches above the top of the pinhole. The stresses reported are those caused by the simulated axial and torsional loads only and do not include the prestress effect of initial interference between pin and pinhole. Also, since the stress distributions and magnitudes are almost the same on either side of the vertical centerline of the pin, only one side is shown on most of the figures and in Table 1. All dimensions shown refer to the model, which is 2.5 times the size of the prototype.

B. Pin Behavior and Effect

1. The three-dimensional distributions of the axial stresses $\bar{\sigma}_y$ on the plane through the top of the pin, Figure 7, shows the effect of the pin on stresses, which without the pin would be fairly uniform. The steep stress gradient along the top of the pin ($x = 1.96$, $z = 0$ to 0.50) is clearly the effect of pivoting of the pin as it transfers load into the bulkhead as shown schematically in the figure accompanying Table 1.

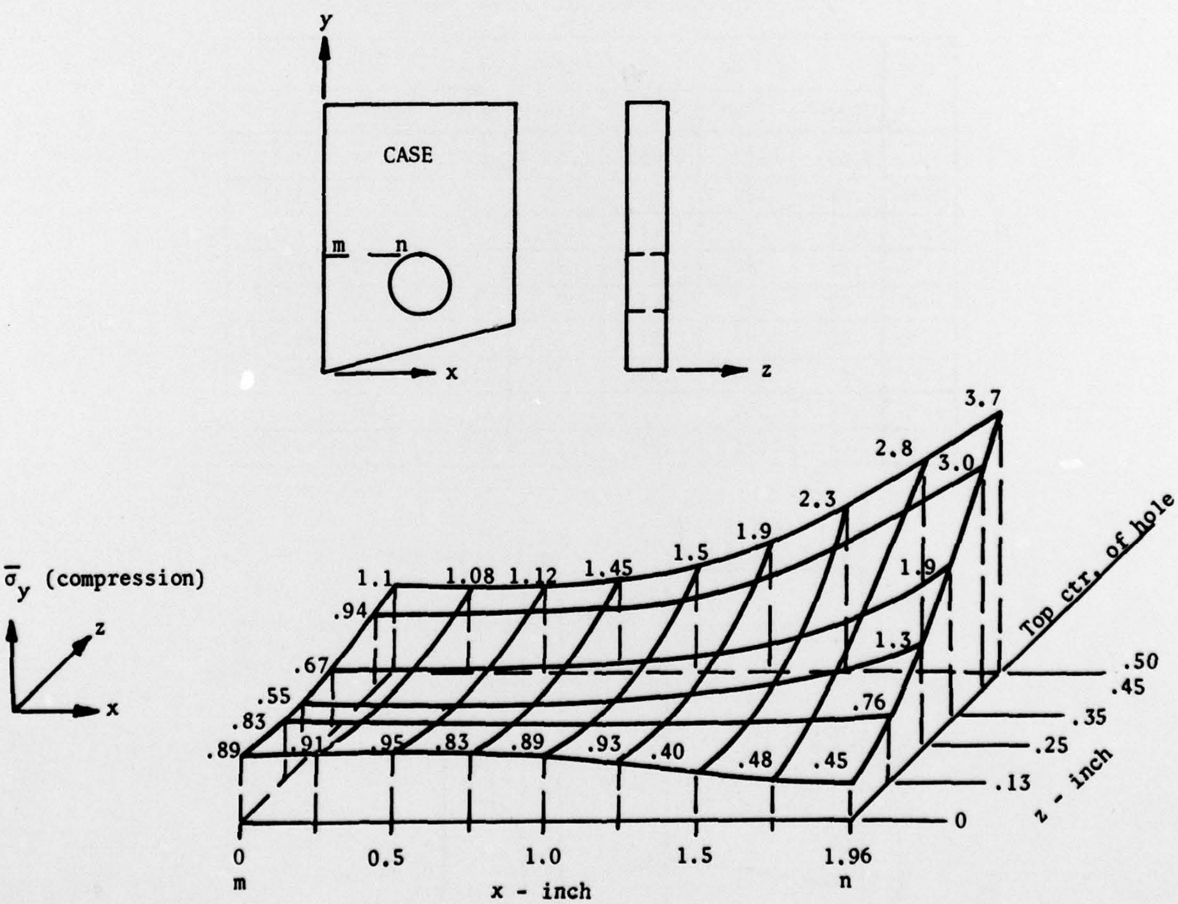


Figure 7. $\bar{\sigma}_y$ stress contours along line mn.

Since the pin in this case is short, with a length-to-diameter ratio of about one, the movement of the pin is a combination primarily of shear deformation and rigid body rotation or pivoting. Of additional phenomenological interest is the fact that contact is maintained between pin and component along the full length of the pin as evidenced by the non-zero normal stress at all points along the top of the pin. With much larger length-to-diameter ratios, i.e., more flexible pins, the effect of bending deformation would become important. However, for the usual pin configurations used, length-to-diameter ratios of up to two or three, the behavior is probably as demonstrated here.

Figure 8 shows the $\bar{\sigma}_y$ stress distribution on the horizontal plane through the center of the pin. The greatly reduced peak stress levels are partially a reflection of the reduction of the total load in the section as the result of the transfer of load through the pin into the other components (the bulkhead).

The distribution in Figure 8 is much more uniform than that in Figure 7, which is probable indication that the effect of pivoting of the pin and the resulting highly concentrated stress effects on the top of the pin dissipate rapidly along the boundary of the pin from the top to the side.

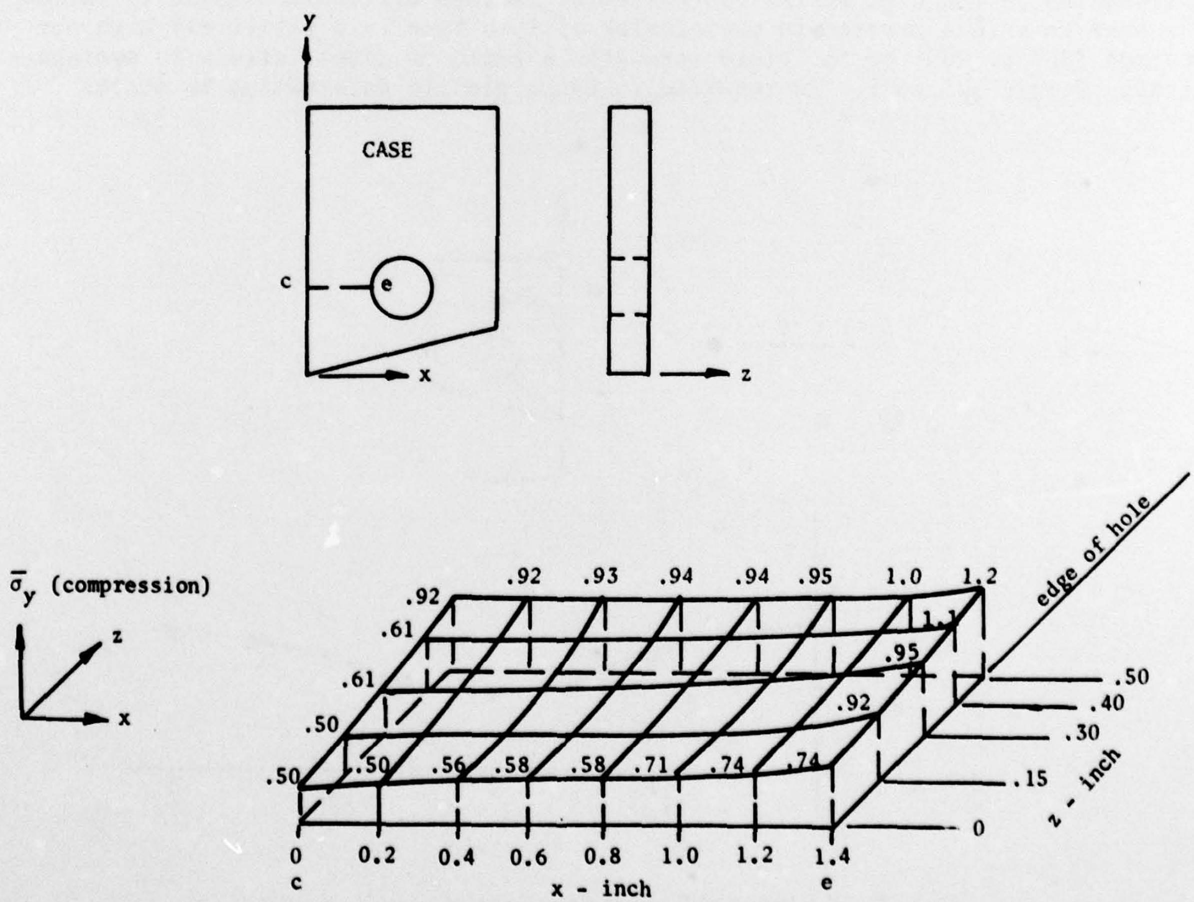


Figure 8. $\bar{\sigma}_y$ stress contours along line ce.

2. The transfer of load through the pin into the bulkhead has the effect of reducing the contact stresses on the joint interface directly below the pin as shown in Figure 9. Integration of the stresses in Figure 8 over the cross-sectional area reveals that one-third of the total load is transferred through the pin into the bulkhead. Redistribution of the uneven stress distribution caused by this transfer has not occurred, probably since the edge distance of the pin from joint interface is very short.

3. Figure 10 shows typical values of the actual-to-average axial stress ratios $\bar{\sigma}_y$ within the case structure. The ratios along the upper portions of the case are all 1.0, indicating that the influence of the pin discontinuity does not extend beyond about one pin diameter above the pin.

The symmetry of the stress magnitudes about the vertical centerline of the pin shows that the effect of the sloping bottom (or the torsion load) on the symmetry is not significant.

C. Stress and Strain Magnitude

The complicated interaction of the pin with the joined components makes the seriousness of the high stress concentration factors difficult to assess. Since the average stress carried in projectiles of this type is a relatively high percentage (85% to 90%) of the yield strength, a ratio of actual stress to average stress of only 1.1 to 1.2 is required to cause plastic deformation to start.

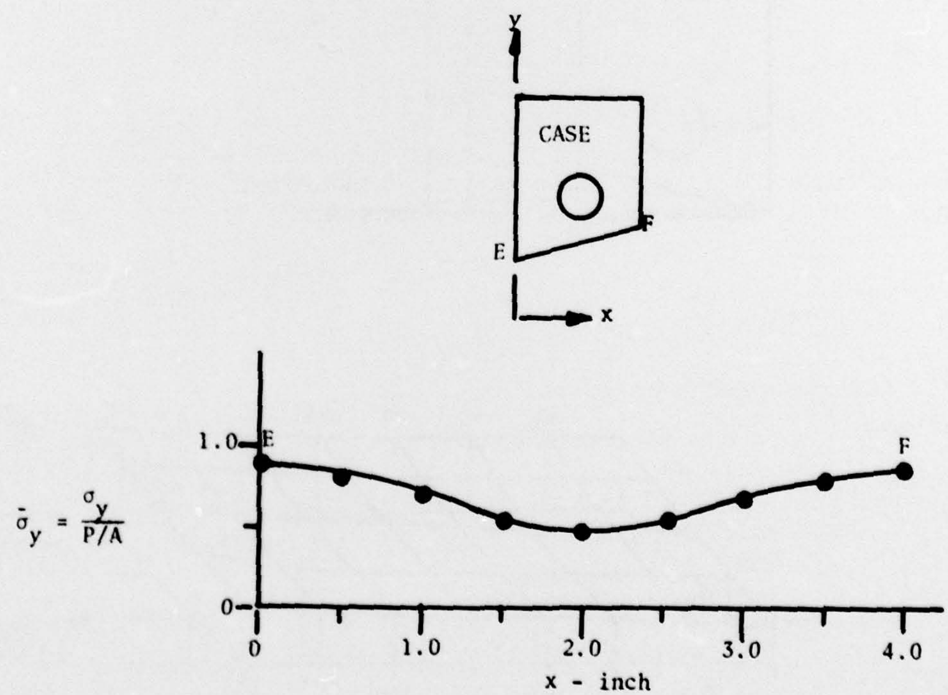


Figure 9. Distribution of $\bar{\sigma}_y$ stress along length of joint EF (z = 0.35").

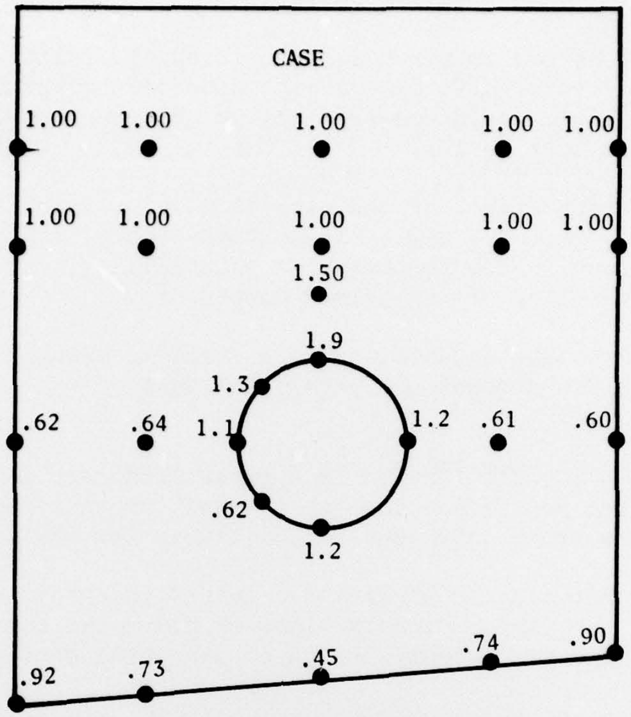


Figure 10. Values of σ_y stress at various locations (z = 0.35").

Since the actual-to-average stress ratios in the joint reach magnitudes well above 1.2 and up to 3.7, the occurrence of plastic strain ranging up to about 2% appears possible under design loading conditions. The actual magnitudes and locations of plastic strain cannot be determined without a three-dimensional elastic-plastic analysis.

The seriousness of such behavior depends on the ability of the material to undergo such large strains without deterioration of its ability to carry other subsequent loads. Tough, ductile materials can safely absorb larger degrees of plastic strain than less ductile, less tough materials.

If the average effective stress over the pin periphery is less than the yield strength of the material, gross yielding over the entire pin contact area would not occur although extensive redistribution of stress and load will occur. If the average effective stress exceeds the yield strength, significant plastic yielding over the entire pin could occur, with excessively high plastic deformation accompanied by serious deterioration of material properties, including cracking. This deterioration would reduce the strength of the structure against subsequent forces in other directions and could possibly lead to catastropic failure.

IV. CONCLUSIONS

Various conclusions can be drawn from the findings relative to the completeness of the study and the significance of the findings to the current problem, and to pin joint design for advanced projectiles or other applications in general. The more urgent conclusions follow.

1. The complicating effect of the pins in a joint leads to high stress gradients and high stress magnitudes which can in turn result in plastic deformation of a magnitude which, depending on the material capabilities, can seriously reduce the structural survivability of the joined components.

2. Scattered light photoelasticity is a straightforward and sufficiently accurate method for three-dimensional stress analysis of complex structural configurations.

3. For photographing the fringes in a given plane section of a specimen, the technique of moving the test model through a fixed concentrated laser beam is more effective than using a broad thin beam which illuminates the entire section.

4. Additional photoelastic studies are needed to obtain data on the elastic stress distributions for various combinations of pin joint configurations to provide a broader basis for preliminary design of pin joint configurations and dimensions.

5. There remains to be demonstrated the feasibility and economy of superimposing applied loads on a frozen stress system, for example, the effect of different pin interference on the overall stress values in a joint.

6. There remains a need for an effective method (either mathematical or experimental) for three-dimensional elastic-plastic analysis of complex joint geometries.

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